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## ELECTRO OPTICAL SIGNAL PROCESSING TECHNIQUES FOR PHASED ARRAY ANTENNAS

**QUARTERLY PROGRESS REPORT P-8/321**
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## ABSTRACT

The investigation of array antenna electro-optical signal processors continues with emphasis placed on the development of a wide-band solid light modulator.

The light modulator bandwidth and the transfer characteristics between input voltage and peak phase deviation of light wave front are obtained experimentally for fused silica light modulators operating in the compression mode. Transfer characteristics are found to be linear as predicted by theory, and bandwidth is found to be greater than 50 per cent of resonant transducer frequency.

Electromechanical cross coupling and ultrasonic beam broadening are investigated for both the shear and compression modes by means of Schlieren techniques. Results show that in a multi-channel configuration, adjacent light modulator channels may be spaced by one transducer width without adverse effects.

First order diffraction patterns are obtained for the fused silica light modulator. Results are consistent with theory showing that no optical distortion is introduced by ultrasonic propagation in fused silica.

## AUTHORIZATION

The research described in this report was performed at the Electronics Research Laboratories of Columbia University. This report was prepared by M. Arm, S. Bernstein, J. Minkoff and N. Wyman.

This project is directed by the Advanced Research Projects Agency of the Department of Defense and is administered by the Air Force Office of Scientific Research under Contract AF 49(638)-1478.

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# I. INTRODUCTION

In order to extend the aperture-bandwidth capability of real-time electro-optical processors for array antennas, the Electronics Research Laboratories of Columbia University has been engaged in the development of a wide-band Debye-Sears light modulator. This research program has as its initial goal the development of a solid light modulator operating at a 100-MHz center frequency with at least a 40-MHz bandwidth.

This report presents a continuation of the theoretical and experimental investigations into the fundamental operating characteristics of wide-band Debye-Sears light modulators employing solid media. The theoretical and experimental research results reported here, together with previous reports,[1,2] show that:

(1) The relationship between input voltage and the resulting peak phase deviation of the light wave front is linear as predicted by theory.

(2) Light modulator bandwidths which are 50 per cent of the resonant frequency of the ultrasonic transducer are easily achieved.

(3) Electromechanical cross coupling and ultrasonic beam-broadening effects will not preclude a multi-channel light-modulator configuration with spacings of the order of one transducer width.

(4) Ultrasonic propagation in a solid does not introduce optical distortion. The results which have been ob-

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[1] For numbered references, see Sec. IV.

tained are equivalent to those obtained with liquid light modulators.

These theoretical and experimental results indicate the feasibility of the solid wide-band light modulator. Future research efforts will be directed towards the practical engineering problems associated with the use of fused silica light modulators in electro-optical processing for array antennas; this includes: experimental determination of the optimal transducer depth to minimize the input electrical power, further investigation of transducer heating effects which have been previously reported, and investigation of the phase coherence properties of piezoelectric quartz transducers.

## II. OPERATING CHARACTERISTICS OF FUSED SILICA LIGHT MODULATORS

The material chosen as the light modulator medium in this research has been fused silica. This material, through its use in the manufacture of acoustic delay lines, has been shown to possess low acoustic loss at high frequencies and is capable of maintaining wide acoustic bandwidths. In addition, it is especially applicable for use as a light modulator medium since it is a transparent substance which can be polished to a high degree of optical flatness.

This section presents the results of experimental investigations into those operating characteristics of fused silica spatial light modulators which are relevant to their application to electro-optical array antenna processing. The specific considerations are:

1. The transfer characteristics between peak input voltage and the resulting peak phase deviation of the light wave front.
2. The bandwidth of the light modulator.
3. Ultrasonic beam-spreading and cross-channel coupling characteristics.
4. The ability of the solid light modulator to produce a first order diffraction pattern as predicted by theory.

### A. MEASUREMENT OF PHASE MODULATION AND LIGHT MODULATION BANDWIDTH

The previous report[2] presented the experimental determination of the bandwidth characteristics and the relationship

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### A. MEASUREMENT OF PHASE MODULATION AND LIGHT MODULATION BANDWIDTH

The previous report[2] presented the experimental determination of the bandwidth characteristics and the relationship between electrical excitation and spatial phase modulation of the light wave-front for fused silica light modulators operating in the shear mode. We now present similar measurements for light modulators employing the compression mode of ultrasonic propagation. These results were obtained with an X-cut piezoelectric crystal which was bonded to a fused silica blank at CUERL.

The experimental set-up for obtaining these measurements is shown in Fig. 1. The photomultiplier produces a current, proportional to the output light intensity at the location of the 5μ scanning slit, which is passed through a load resistor $R_L$. Thus, in the actual measurement procedure, a voltage V is measured across $R_L$ which is proportional to the light intensity at the position of the scanning slit.

In order to be of use in electro-optical array antenna processing, the light modulator must be capable of maintaining a bandwidth which is at least 50 per cent of the resonant transducer frequency. The bandpass characteristics were determined by measuring the peak first order light intensity as the frequency of the input electrical signal was varied, with the input signal amplitude being held at a fixed value. It was found that, although a 100-MHz piezoelectric crystal was used, the bonding process in this case lowered the transducers resonant frequency to approximately 85 MHz. The bandwidth, however, is seen in Fig. 2 to be approximately 55 MHz which, using the 50 per cent bandwidth criterion, is somewhat more than sufficient for electro-optical processing.

In measuring the relationship between $V_m$ and $\psi_m$, we make use of the fact that, under the condition that $\psi_m \leq 0.2$ radians, the ratio of first order to zero order light intensity[3] is $\frac{\psi_m^2}{4}$ : 1. Thus if the detector output voltages which are

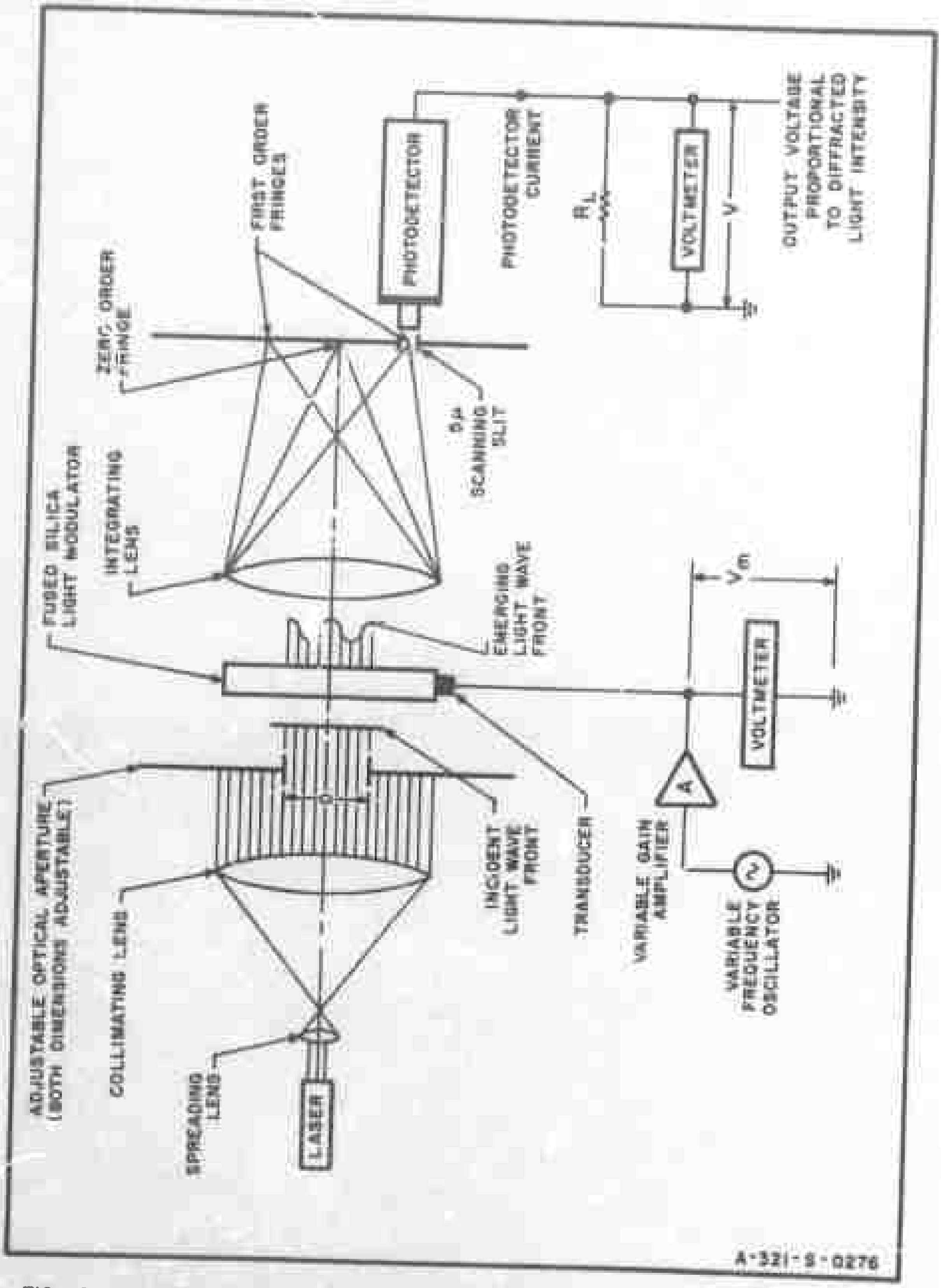



FIG. 1 SYSTEM FOR MEASURING DIFFRACTED LIGHT INTENSITY.

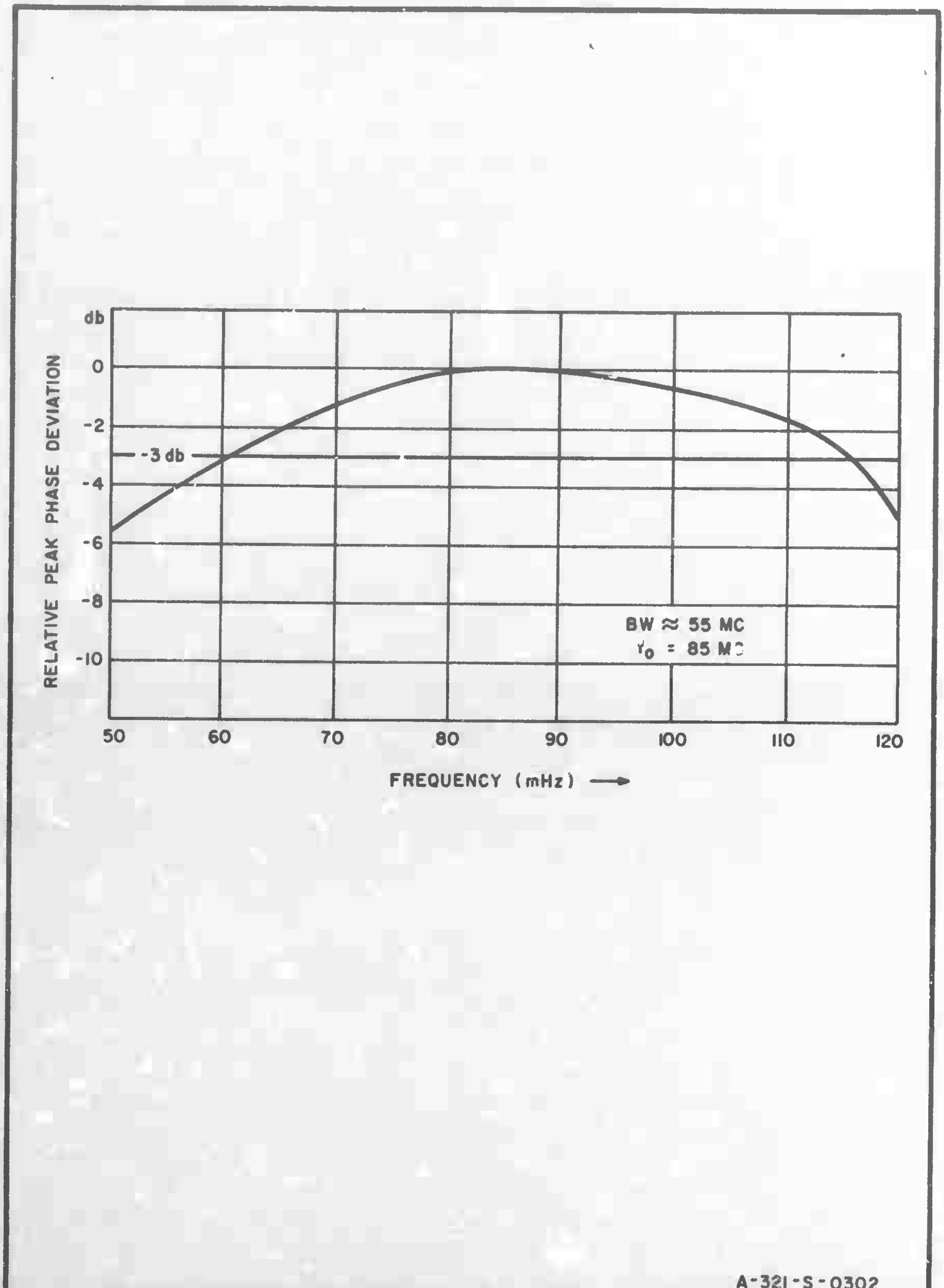



FIG. 2 BANDPASS CHARACTERISTICS OF FUSED SILICA LIGHT-MODULATOR EMPLOYING ULTRASONIC COMPRESSION MODE

measured when the scanning slit is positioned at the center of the zero order and first order diffraction fringes are, respectively, $V_o$ and $V_1$, then:

$$\frac{\psi_m^2}{4} = \frac{V_1}{V_o}$$

from which $\psi_m$ may be determined.

The theoretical relationship between $\psi_m$ and $V_m$ for the compression mode of ultrasonic propagation in fused silica (assuming polarization of the incident light perpendicular to the direction of ultrasonic propagation) has been shown to be:[1]

$$\psi_m = \frac{2\pi L n_o^2 p k}{\lambda E} V_m$$

where:

$n_o$ = unstressed refractive index

$L$ = active transducer depth (dimension of back electrode along light path)

$\lambda$ = light wavelength

$p$ = Neumann's "p" constant

$E$ = Young's modulus

$k$ = electromechanical coupling coefficient of piezoelectric transducer.

It is seen therefore that, theoretically, a linear relationship exists between $\psi_m$ and $V_m$. Although the average values of the above physical constants have been measured to sufficient accuracy to be useful in predicting approximate voltage requirements, their precise values will depend on the exact composition of the individual piece of fused silica. In addition, the available value of the photoelastic constant p, which aside from exhibiting possible variations with the composition of the medium is also a function of light wavelength, has been measured by Primak and Post[4] for a 0.5890-μ light source. In these experiments however, the light source wavelength was 0.6328 μ. It is therefore possible to obtain only an approximate theoretical value of the constant of proportionality between $\psi_m$ and $V_m$.

The experimental measurements of $\psi_m$ as a function of $V_m$ are presented in Fig. 3. Included in the same figure is the theoretical relationship which was obtained using the available values of the relevant physical constants. It is seen that the experimentally determined relationship between $\psi_m$ and $V_m$ is linear within experimental error, and that the input voltage requirements for specific values of peak phase deviation can be approximately predicted.

## B. ULTRASONIC BEAM BROADENING AND CROSS CHANNEL COUPLING

It has been shown[3] that the maximum number of light modulator channels which may be fitted into an optical aperture of width W is given by:

$$N = \frac{W}{2}\sqrt{\frac{f}{DS}} \qquad \text{(II-1)}$$

where:

f = frequency of electrical signal exciting piezoelectric transducer

S = ultrasonic velocity of propagation

D = aperture length along the direction of sonic propagation.

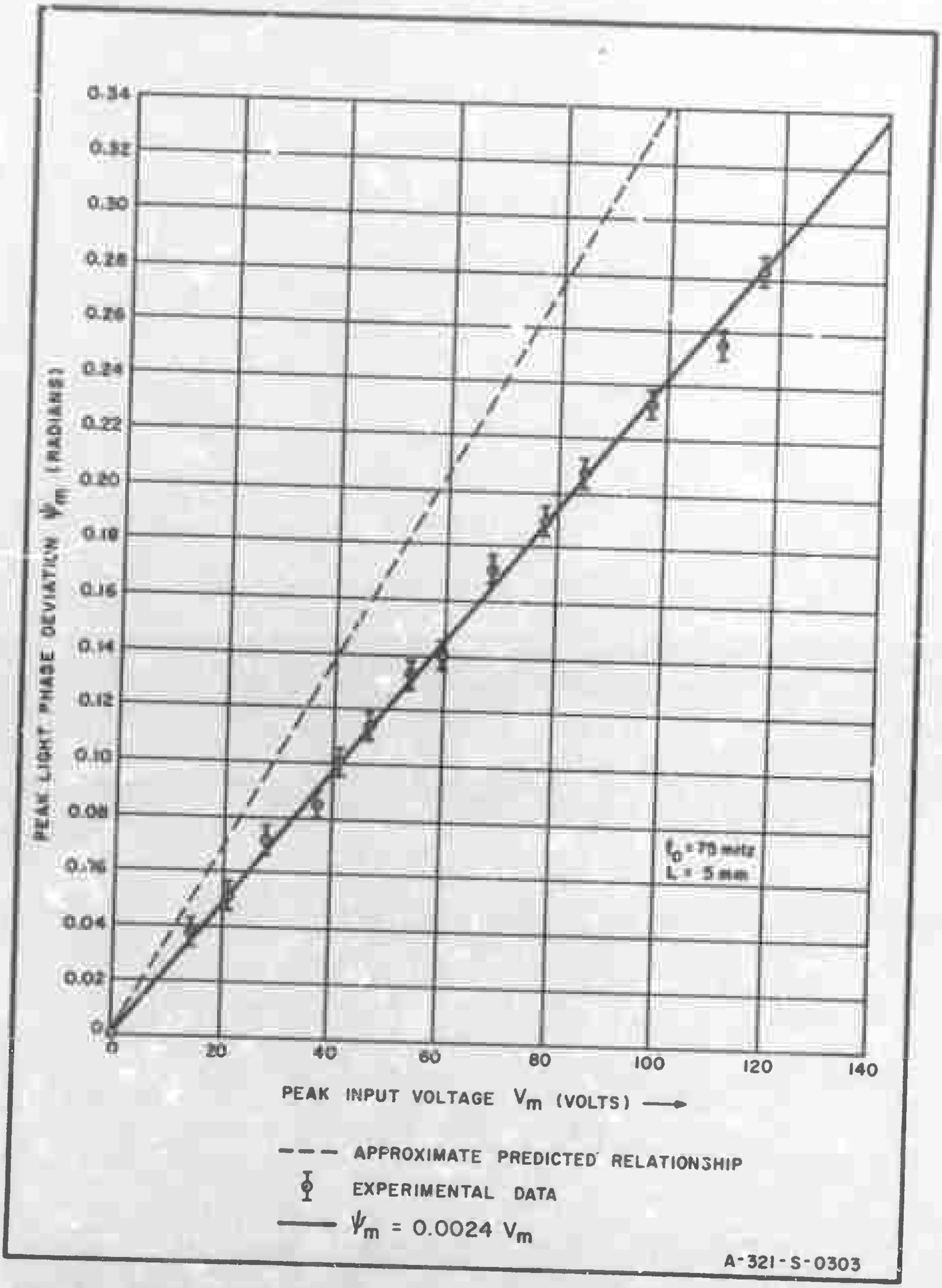



FIG. 3 PEAK PHASE MODULATION vs. PEAK INPUT VOLTAGE FOR A FUSED SILICA LIGHT-MODULATOR EMPLOYING COMPRESSION MODE TRANSDUCER

This relationship has been derived through consideration of ultrasonic diffraction effects. It has been shown[5] that, for longitudinal waves, ultrasonic propagation in a solid follows approximately the same laws as electromagnetic propagation in space. For this analysis it has been assumed[3] that, due to ultrasonic diffraction, the beam actually spreads as is shown in Fig. 4. The far field spreading angle $\theta_s$ is given by:

$$\theta_s = \frac{2\lambda_s}{b}$$

where b = width of transducer and the spreading width $w_s$ (Fig. 4) is thus:

$$w_s = D\theta_s = \frac{2D\lambda_s}{b} .$$

It is seen therefore that the maximum number of channels which may be fitted into any given aperture of width W is limited by the transducer spacing which must be such that any "cross talk" between adjacent channels due to ultrasonic beam spreading is eliminated. One criterion which has been employed successfully[3] is to limit the number of channels such that:

$$W = w_s N = \frac{2D\lambda_s}{b} N . \qquad \text{(II-2)}$$

and then to separate each of the adjacent channels by a transducer width such that:

$$W = 2bN . \qquad \text{(II-3)}$$

Thus Eq. II-1 is obtained from II-2 and II-3.

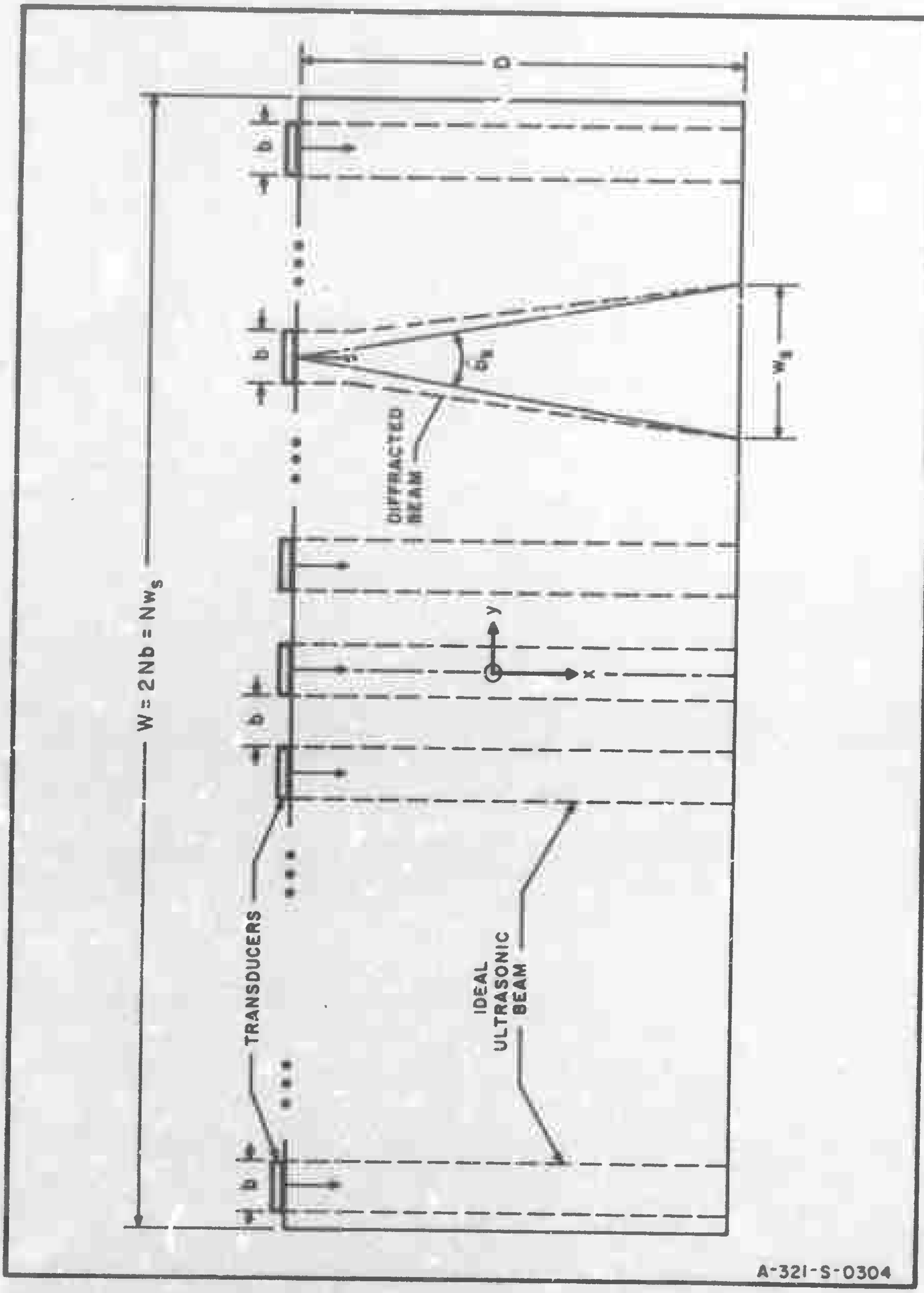



FIG. 4 ULTRASONIC DIFFRACTION IN A SPATIALLY MULTIPLEXED, DEBYE-SEARS LIGHT MODULATOR

This latter restriction (Eq. (II-3)) was found to be necessary to minimize any possible electrical and mechanical coupling effects which may exist at the transducers.

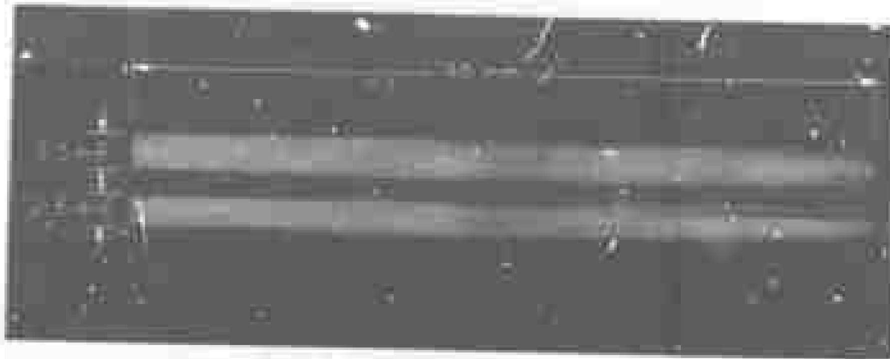
The relationship expressed in Eq.(II-1) is now verified for fused silica light modulators by the experimental results presented in Figs. 5 a,b,c and 6 a,b,c which are Schlieren photographs of ultrasonic shear compression waves, respectively.

In Figs. 5a and 6a, the photographs, which were deliberately overexposed, were obtained with a 75-MHz signal simultaneously exciting two transducers which were 3-mm wide and separate by a distance of 2 mm. It is seen that, for both the shear and compression modes, the beams remain sufficiently collimated to avoid "cross talk." In examining electro-mechanical cross channel coupling, a photograph was taken of each configuration using a low excitation and a 1-second exposure (Figs. 5b and 6b). One electrical connection was then removed, leaving the back electrode in place, and a photograph was taken using an electrical excitation 10 times as large with a 3-second exposure (Figs. 5c and 6c). Now it is evident that any deleterious electro-mechanical cross coupling would cause a spurious signal to be generated at the unexcited electrode. Since, however, (by Figs. 5b and 6b) it is possible to observe an acoustic wave resulting from an excitation one tenth of that which produced Figs. 5c and 6c, then, by linearity of $\psi_m$ and $V_m$, any diffracted light intensity resulting from electro-mechanical cross coupling is verified to be supressed by more than 20 db.

C. MEASUREMENT OF FIRST ORDER LIGHT INTENSITY DISTRIBUTION

One of the essential requirements of the light modulators used in the electro-optical array antenna processor is that

DIRECTION OF ULTRASONIC PROPAGATION ⟶



5a — BOTH TRANSDUCERS EXCITED
INPUT VOLTAGE = $V_{in}$
EXPOSURE TIME = T

5b — BOTH TRANSDUCERS EXCITED
INPUT VOLTAGE = $V_{in}/10$
EXPOSURE TIME = T

5c — ONE TRANSDUCER EXCITED
INPUT VOLTAGE = $V_{in}$
EXPOSURE TIME = 3T

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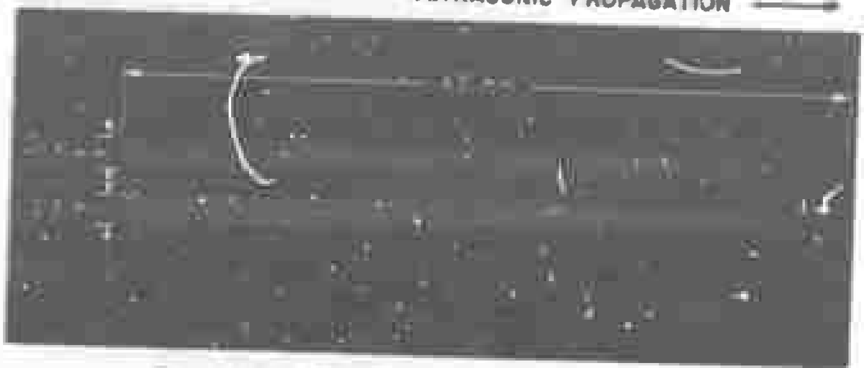
FIG. 5 SHEAR MODE TRANSDUCERS — EXPERIMENTAL SCHLIEREN PHOTOGRAPHIC STUDY OF ULTRASONIC BEAM BROADENING AND ELECTRO-MECHANICAL CROSS-COUPLING.

DIRECTION OF ULTRASONIC PROPAGATION ⟶



6a – BOTH TRANSDUCERS EXCITED
INPUT VOLTAGE = $V_{in}$
EXPOSURE TIME = T

6b – BOTH TRANSDUCERS EXCITED
INPUT VOLTAGE = $V_{in}/10$
EXPOSURE TIME = T

6c – ONE TRANSDUCER EXCITED
INPUT VOLTAGE = $V_{in}$
EXPOSURE TIME = 3T

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FIG. 6 COMPRESSION MODE TRANSDUCERS – EXPERIMENTAL SCHLIEREN PHOTOGRAPHIC STUDY OF ULTRASONIC BEAM BROADENING AND ELECTRO-MECHANICAL CROSS-COUPLING.

they introduce no optical distortion resulting from ultrasonic propagation in the light modulator medium, i.e., the acoustic wave must act as a pure diffraction grating producing a first order diffraction pattern consistent with the aperture dimensions and the frequency of excitation. For an aperture of length D (dimension along direction of sonic propagation) and an electrical excitation of frequency f, the first order diffracted light intensity as a function of the output variable u should be proportional to:

$$\left[\frac{\sin \pi D(u - f_s)}{\pi D(u - f_s)}\right]^2$$

where:

$$f_s = \frac{f}{S} = \text{spatial frequency (cycles per meter)}$$

$$S = \text{sonic velocity} \quad .$$

The first order intensity therefore is, theoretically, a replica of the zero order pattern, with its peak occurring at the point:

$$u = f_s \quad .$$

The output variable u is given by:

$$u = \frac{f}{S} = \frac{x_1}{\lambda F}$$

where:

$x_1$ = linear displacement of first order peak intensity

$\lambda$ = light wavelength = $6328 \times 10^{-10}$m

F = focal length of integrating lens = 1 m .

In this measurement:

f = 70 MHz

S = sonic velocity 5968 m/sec

and the theoretical displacement of peak first order intensity is therefore:

$$x_1 = 7.42 \text{ mm} \quad .$$

Using the scanning apparatus shown schematically in Fig. 7, the first order light intensity distribution was recorded (Fig. 8) using a phase deviation of $\psi_m = 0.2$ radians. The aperture dimensions in this case were:

D = 30 mm (length of aperture along dimension of sonic propagation)

b = 4 mm (width of aperture = width of transducer).

Since the direction of sonic propagation is in the x direction, only the output distribution as a function of the output variable u is of interest. The location of peak first order intensity was found experimentally to be:

$$x_1 = 7.5 \text{ mm} \quad .$$

This distribution may be compared with that of the zero order as shown in Fig. 9. It is seen that the light intensity at the first nulls is 26 db below the peak in the zero order pattern as compared with approximately 22 db below peak intensity in the first order. This may be caused by errors introduced by the integrating lens which must operate off its

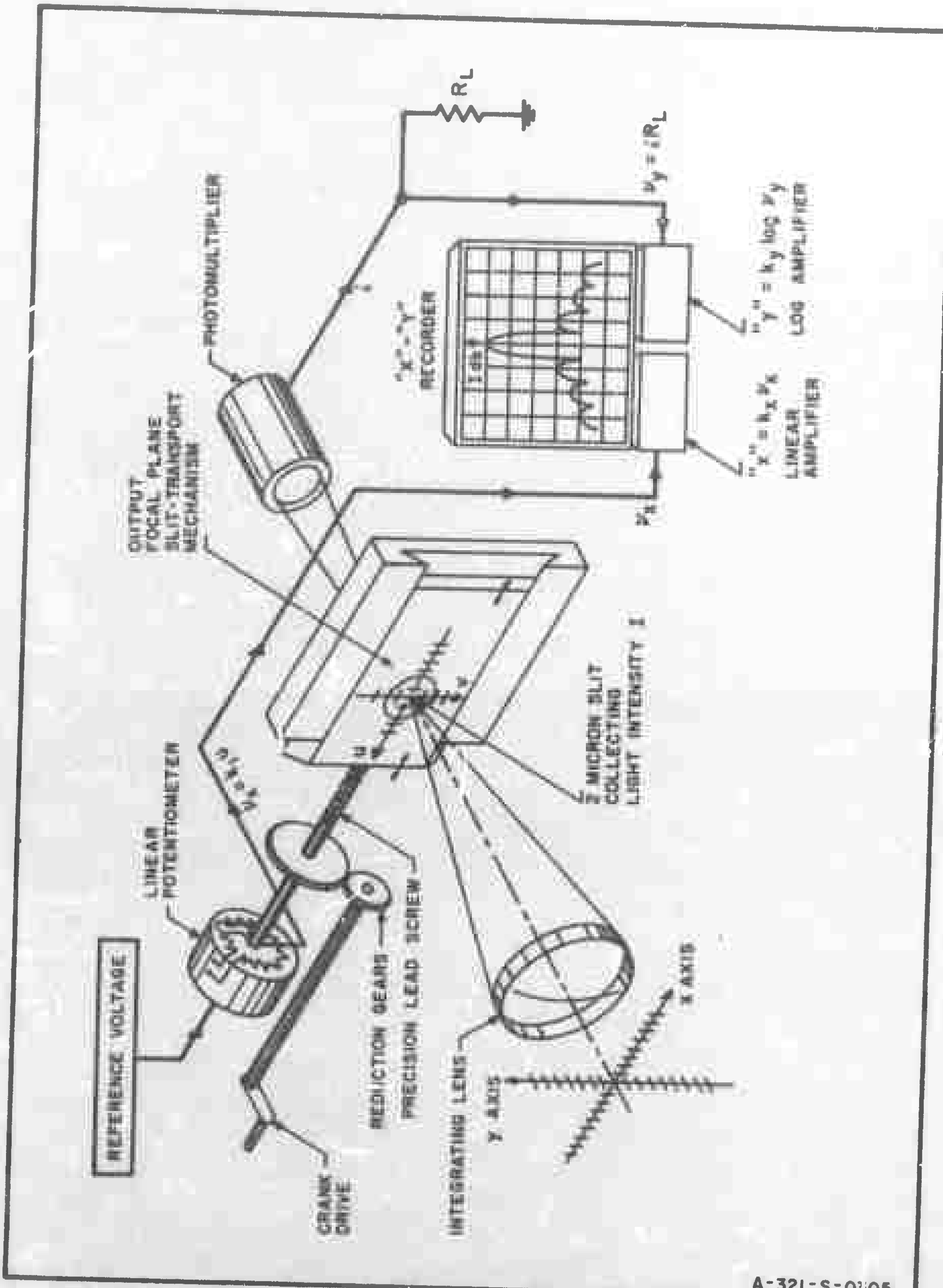


FIG. 7 EXPERIMENTAL READOUT MECHANISM DIAGRAM.

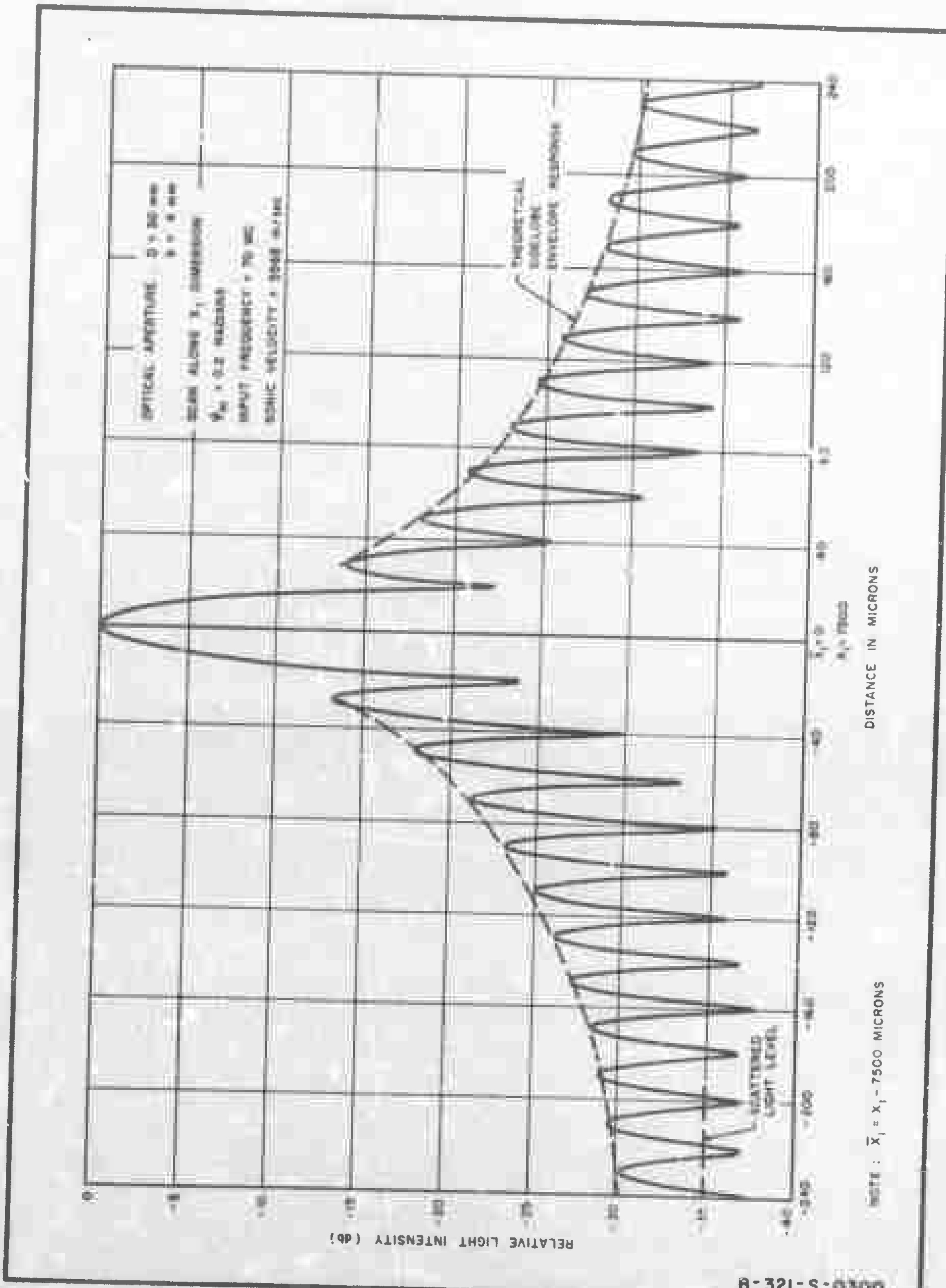


FIG. 8 POSITIVE FIRST ORDER LIGHT INTENSITY

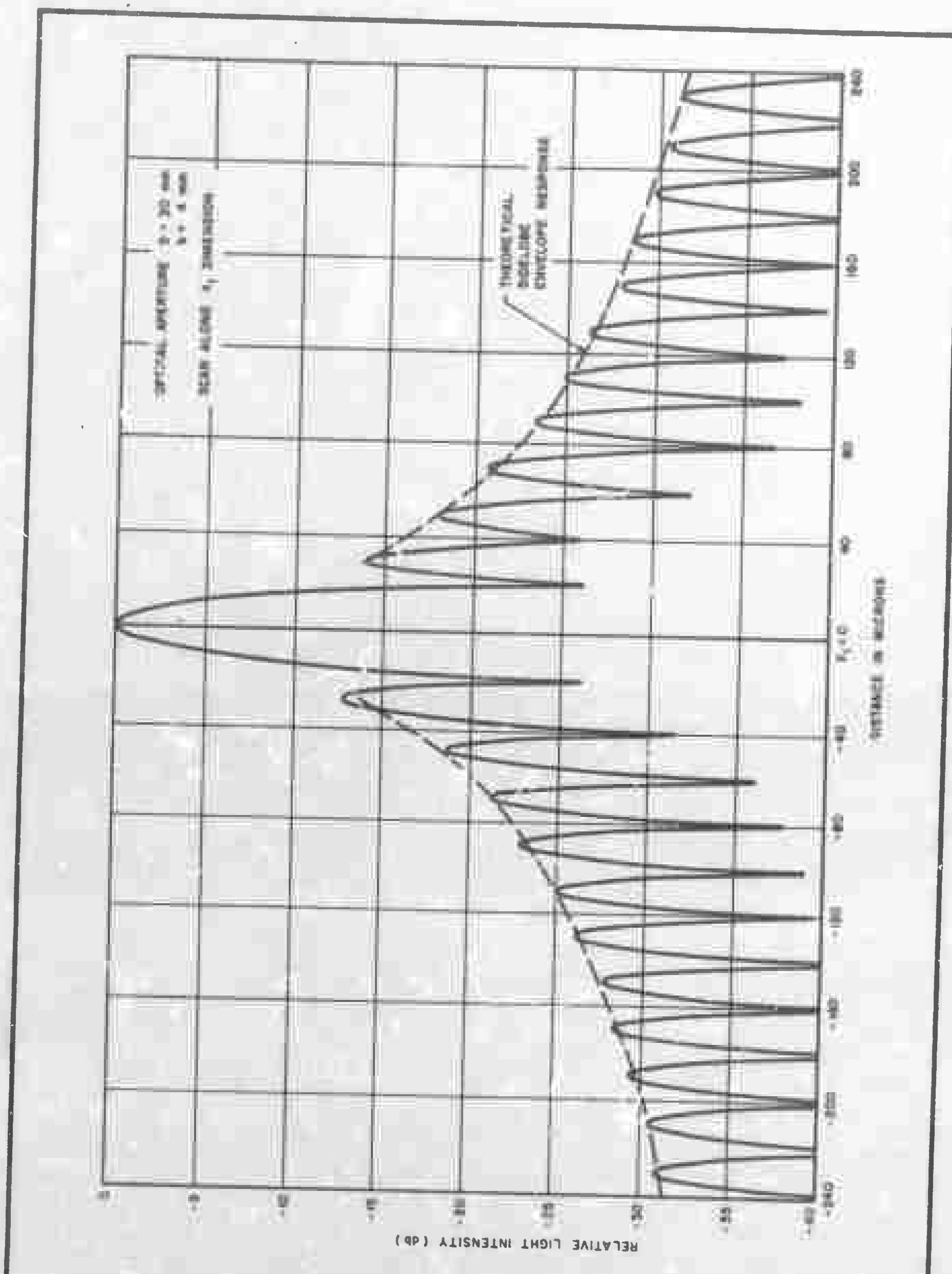


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FIG. 9 ZERO ORDER LIGHT INTENSITY

optic axis in producing the first order distribution. In general, however, it is seen that the first order diffraction pattern is a nearly ideal replica of the zero order.

## III. MEASUREMENT OF SCATTERED LIGHT INTENSITY

An optical aperture of height D will produce a zero order diffraction pattern whose light distribution as a function of the output variable u will be given by (Fig. 10):

$$I_o(u) = \left(\frac{k \sin \pi Du}{\pi Du}\right)^2$$

where k = constant.

Thus the ideal light level, as a function of u, can be defined as

$$L(u) = \left(\frac{k}{\pi Du}\right)^2 .$$

It is seen that $L(u)$ is the envelope of the side lobes of $I_o(u)$.

In general, the measured light level will be somewhat higher then that given by $L(u)$ resulting from light which is scattered because of imperfections in the lens surfaces. Since scattered light tends to obscure the location of peak first order intensity, thus decreasing the dynamic range of the system, it is of course desirable to keep the light level as close as is possible to the ideal in the output region of interest. A measurement of the scattered light in this optical system is presented in Fig. 11 along with the theoretical level. The output region of interest is noted in Fig. 11. It is seen that the scattered light level in this region is approximately 5 db above the theoretical value.

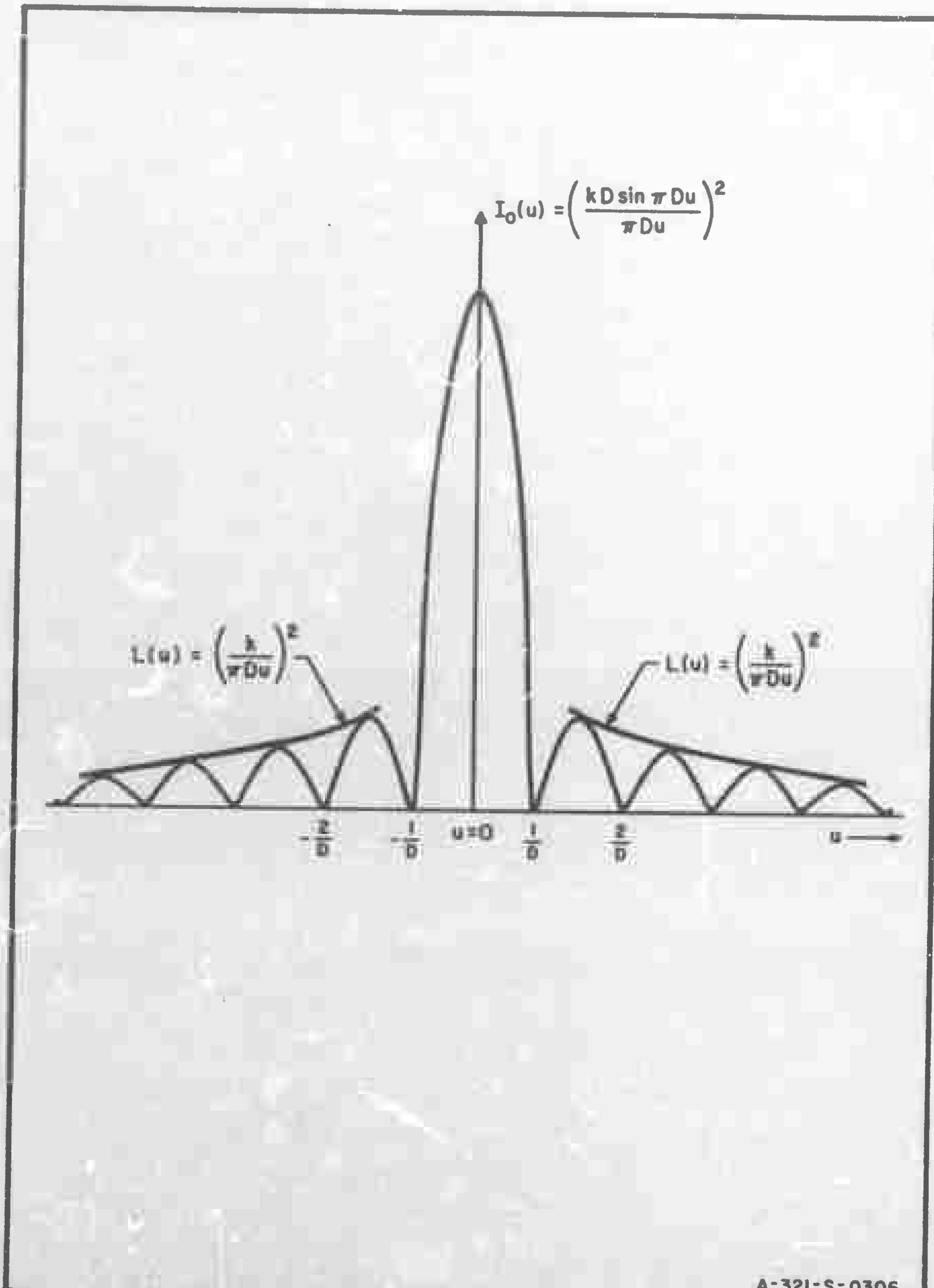


FIG. 10 IDEAL ZERO ORDER LIGHT INTENSITY DISTRIBUTION FOR APERTURE OF LENGTH D

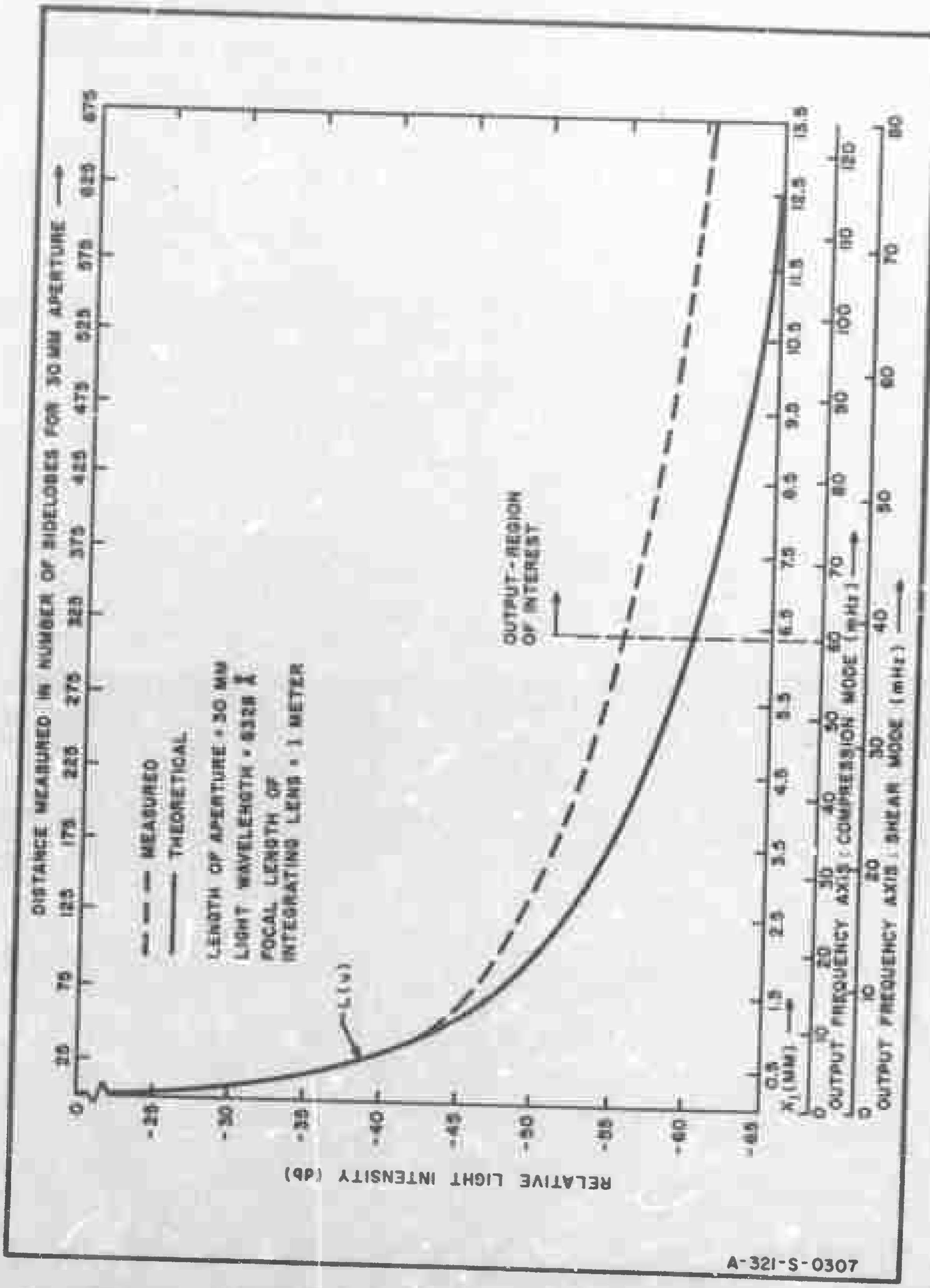


FIG. II SCATTERED LIGHT LEVEL OF OPTICAL SYSTEM

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